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EVALUATION OF THE RECHARGE COMPONENT OF THE PILOT CONTAINMENT SYSTEM AT THE NORTH BOUNDARY OF ROCKY MOUNTAIN ARSENAL

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13. ABSTRACT *(Maximum 200 words)*
THIS REPORT IS ONE OF FIELD TESTS CONDUCTED AT RMA OF DESIGN CONCEPTS FOR THE RECHARGE COMPONENT OF THE PILOT CONTAINMENT SYSTEM AT THE NORTH BOUNDARY. TAKING INTO CONSIDERATION: (A) EASE OF MAINTENANCE AND OPERATION, (B) ABILITY TO ACQUIRE ACCURATE OPERATIONAL TEST DATA, (C) THE NUMBER OF RECHARGE POINTS REQUIRED TO REPRODUCE THE NATURAL AQUIFER DISTRIBUTION, AND (D) THE ABILITY TO BALANCE THE DEWATERING AND RECHARGE OPERATIONS TO ACCOMMODATE SEASONAL VARIATION ON AQUIFER FLOW, IT IS RECOMMENDED THAT A SYSTEM OF 12, 16 INCH DIAMETER WELLS, INSTALLED AND CONSISTENT WITH PRACTICES NORMALLY USED IN DEVELOPING A WATER SUPPLY WELL, BE EMPLOYED IN THE NORTH BOUNDARY PILOT CONTAINMENT SYSTEM TO RECHARGE THE WATER FROM THE WATER TREATMENT FACILITY BACK INTO THE AQUIFER.

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Commerce City, Colorado 80022

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6 Jul 77

SUBJECT: Evaluation of the Recharge Component of the Pilot Containment System at the North Boundary of RMA

Project Manager for Chemical Demil
and Installation Restoration
ATTN: DRCPM-DRR
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Aberdeen Proving Ground, Maryland 21010

Inclosed for your review and information is a report of field tests conducted at RMA of design concepts for the recharge component of the pilot containment system at the north boundary. As a result of these tests, a system of twelve 16" diameter wells has been adopted as the recharge component and will be incorporated into the total design package. This approach has been discussed with Mr. Wynne and Captain Kolmer of your office.

1 Incl
as

JOHN P. BYRNE
COL, CmlC
Commanding

CF:
ARRCOM, ATTN:
DRSAR-AS &
DRSAR-IS

[redacted]

AMERICAN REVOLUTION BICENTENNIAL 1776-1976

EVALUATION OF THE RECHARGE COMPONENT OF THE PILOT CONTAINMENT SYSTEM AT THE NORTH BOUNDARY OF ROCKY MOUNTAIN ARSENAL

prepared by

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1 JUL 77

ROCKY MOUNTAIN ARSENAL
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EVALUATION OF THE RECHARGE
COMPONENT OF THE PILOT
CONTAINMENT SYSTEM AT THE
NORTH BOUNDARY OF ROCKY MOUNTAIN ARSENAL

APPROVED: John P. Byrne

JOHN P. BYRNE, COL, CmlC
Commanding

1 JUL 77

ILLUSTRATIONS

I. INTRODUCTION

A. General

1. One of the major components of the pilot containment system along the north boundary of RMA is the one dealing with recharge. Briefly, the function of the pilot containment system is: (1) To remove contaminated groundwater from the near surface aquifer that occurs at RMA; (2) To process this water through a treatment system to remove the organic contaminants from it; and (3) To reintroduce the treated water into the aquifer.

2. The pilot containment system is a test program to demonstrate the feasibility of groundwater removal, treatment and recharge, and is being conducted to comply with the State of Colorado Cease and Desist Order issued against RMA requiring the cessation of discharging contaminated groundwater off the Arsenal. It is important to emphasize that it is a pilot system covering only 1,500 linear feet on the north boundary, and it is not capable, nor has it been designed to control the migration of contaminants across the entire north boundary.

3. Recharge systems are not a common aspect of groundwater related projects. The two most common uses of recharge systems are along coastlines where salt water intrusion into fresh aquifers poses a threat and in the oil industry where salt water associated with oil production is reinjected back into the producing formation. In this instance, the injection serves a two-fold purpose: (1) It provides a solution for the disposal of potentially large volumes of saline water and (2) The injection of the water also provides an additional driving force in moving the crude oil to the well. In both these instances, the water is generally injected into subsurface formation under pressure.

4. The recharge system to be used at RMA is significantly different than described above in that: (1) The water being recharged will only be under that pressure developed by the hydraulic head maintained at the well bore and (2) The volume of water introducted into the aquifer equals only that which would flow normally through the system.

5. Extensive literature searches and discussion with USGS and WES personnel have shown that recharge systems are not well understood in a mathematical sense. Much of the work, where artificial recharge into the surface has been attempted, is site specific and empirical in nature. That is, recharge practices are modified as needed during operation to achieve the desired goals.

B. Recharge Plan

1. The test plan originally proposed by RMA to evaluate a design concept for that recharge portion of the containment system consisted of large-diameter bores completed to a depth of approximately two feet into the aquifer along the proposed recharge line (Figure 1). Three sites were chosen (Figure 2); one site is near the west end of the proposed alignment where the aquifer is thin, and two bores were placed 100 feet apart in the thickest part of the aquifer (Figure 3). A recharge trench design was also evaluated (Figure 4).

2. The recharge test was conducted in two phases: (1) A slug test in which each bore was filled with water to a level equal to the ground surface and the drop in hydraulic head measured versus time and (2) A constant-Q test in which each bore was charged at a constant rate. In this second phase, time, volume of water, and head change were monitored. Graphical plots of total volume of water versus head change and time versus head change can be used to give insight into the efficiency of the recharge method.

3. Following the initial testing in bores "A," "B," and "C" and the trench, another series of constant-Q tests were performed. It was felt that the initial test data, as outlined in the next section, was suspect because of the high potential of siltation problems from the bog water used for recharge and the effect of variation of in situ permeability of the aquifer material. The manner in which the bores and trench were designed and constructed means that water infiltrating into the aquifer is essentially in a vertical direction. In sediment such as that which comprises the aquifer, the vertical permeability is commonly 80 to 90 percent lower than the horizontal permeability. This simply means that the aquifer cannot readily transmit as much water in a vertical path as in a horizontal path over a given period of time.

4. Prior to initiating this second phase of recharge analyses, bores "B" and "C" and the trench were cleaned. This cleaning consisted of utilizing a contractor-operated sand bucket to muck out the sediments in the two bores. This had the effect of removing any silt and clay-clogged sand at the bottom of the bore. In addition, the removal of fairly large amounts of aquifer material from the bores effectively negated the horizontal to vertical permeability differences in the vicinity of the bore. Cleaning of the bottom sediment in the trench was accomplished primarily by a surging method. This operation consisted of jetting clean water through the upper two to four feet of

the exposed aquifer, forcing the finer grained material into suspension. The muddy water was then removed by pumping. The results of both aspects of the recharge program are discussed below in the section on test analyses.

C. Mathematical Analysis of Recharge Data

1. As discussed previously, analysis of recharge data with respect to specific programs is largely empirical in nature. Extensive literature searches and discussions with other professional geologists and hydrologists show that rigorous mathematical analysis of recharge systems has not been developed. Dewatering systems and well field design, on the other hand, have been sufficiently studied that an extensive base has been developed for mathematical treatment.

2. In a theoretical sense, recharge is just the reverse of dewatering. For example, in many dewatering well analyses, the image well concept is used to define aquifer boundary conditions. An image well is an imaginary well introduced to create a hydraulic flow system which will be equivalent to the effects of a known physical boundary in the flow system. Using this concept then, one can evaluate a recharge well on the same basis as a dewatering well. The implication is that if a given dewatering well is capable of yielding so much water under a given set of conditions, a recharge well can yield an equivalent amount of water back to the aquifer under the same set of conditions. The deviation of actual results from the predicted results based on applying discharging well theory to recharge is an indication of the limits to which mathematical analyses can be used.

3. Given the limitations of applying well flow hydraulics to recharge, their utility is not to be discounted. Their utility lies not so much in the absolute data derived from recharge analyses, but more on the order of comparing one recharge design, or method, to another.

4. In the section dealing with the recharge test analyses, mathematical analysis is used and compared with the empirical data derived from the actual testing.

II. TEST PROCEDURES

A. The initial testing of bores "A," "B," and "C" consisted of performing a slug test on each bore and a constant-Q test. The details of these tests are described in the IR Program Status Review of May 77. Briefly, the constant-Q test consisted of introducing water into the bores at constant rates over a period of as much as 72 hours. The source

of water used was from the bog in Section 24 along the north boundary of RMA. The volume of water entering the bore, time, and the head rise were monitored at intervals over the testing period.

III. TEST ANALYSES

A. Empirical Analysis

1. The most common graphic presentations used in well hydraulics are plots of total volume of water introduced versus change in hydraulic head and change in hydraulic head versus time. A plot of head change versus time is particularly significant because this is the data most often used in mathematical analyses. Figures 5 and 6 compare hydraulic head change with time. The injection rate for bore "C" was initially about 10 gpm and reduced to 3 gpm about 800 minutes into the test. Over the total test time, the average recharge rate was 8.5 gpm. The head rise in this bore exceeded 15 feet, and water overflowed onto the ground surface. The recharge rate in bore "B" was maintained around 9.5 gpm over a 1,500 minute test period. Total head rise over this interval was 10.56 feet. An initial test on the trench showed that a recharge rate of 3 gpm could not be maintained without excessive head rise. Excessive head rise is defined to be where water overflows the top of the recharge container. Figures 7 and 8 compare head change in bores "B" and "C" with total volume of water.

2. As discussed in a previous section, it was felt that these rapid and excessive head rises were due to siltation and vertical permeability effects.

3. Figures 9 and 10 compare hydraulic head change to time and total volume of water. These data are based on a recharge test performed subsequent to cleaning out the bore using a sand bucket as described previously. The test was run over a period of approximately 50 hours, and the average recharge rate was 6.8 gpm. Maximum head change was 4.75 feet. Comparing Figure 10 to Figure 7, it can be seen that the cleaning procedure resulted in the increased capacity of the bore to uptake a greater volume with a significantly lower head rise.

4. A recharge test rerun on the trench following the surge and pump procedure showed a substantial improvement in its capacity to recharge water into the aquifer without excessive head rise (Figures 11 and 12). In this second test on the trench, the capacity was over 30,000 gallons, at an average recharge rate of 7.4 gpm with a maximum head rise of 4.22 feet. This change in infiltration rate versus head rise shows a signficiant improvement over the 3 gpm rate achived in the initial test.

5. The principal reason for testing both bore and trench recharge was to evaluate the two different methods. In the course of evaluating the alternatives, it was felt that an additional test procedure be utilized. This involved installing a large diameter well screen in the bore, penetrating the entire thickness of the aquifer material (Figure 13). The principal purpose of evaluating this design was to determine if a significant increase in recharge efficiency could be realized with a recharge well as opposed to a recharge bore or trench. Accordingly, 16-inch diameter screens were placed in the bottoms of both bores "B" and "C." To ensure that the maximum efficiency was achieved with this design, these wells were developed using methods consistent with practices normally used in developing a water supply well. Figures 14 and 15 show the results of the recharge test on bore/well "B." A total of 66,390 gallons was recharged into this design setup over a period of about 75 hours, with a maximum head change of 4.45 feet. The average recharge rate over the test interval was 14.5 gpm.

6. A comparison of the slopes of the lines for Figures 5, 9, and 14 or Figures 8, 10, and 15 show that the installation of the screen results in a significant increase in infiltration rate.

B. Mathematical Analyses

1. Present knowledge of mathematical solutions to groundwater flow problems is the result of numerous investigations over the past 100 years. The equations developed for solving well flow problems were developed primarily to aid in the design and construction of groundwater supplies. The two most commonly used solutions to solving well flow problems are the Theis and Jacob methods for nonequilibrium flow.

2. The data used to solve the respective Theis or Jacob equations are derived from pump tests. These pump tests generally utilize a constant discharge from the well (constant-Q test) and draw-

down of the water level is measured in observation wells at selected distances from the pumping well. Solution of the equations permits the determination of the formation constants, T (transmissivity) and S (storage coefficient). Transmissivity is defined as the rate of flow of water through a vertical strip of unit width which extends the entire saturated thickness of the aquifer under unit hydraulic gradient. The storage coefficient of an aquifer is the volume of water it releases or takes into storage per unit surface area of the aquifer per unit change in component of head normal to that surface. Once the constants T and S have been determined, predictions can be made as to how much water is in storage in the aquifer; how much water in a single well, or a combination of wells, can be expected to yield; and what the drawn down of water levels in the aquifer will be for a given period of time.

3. Although both the Theis and Jacob equations are principally used for flow from a well, with caution they can be used in dealing with flow into a well. In discussions with USGS personnel, the question arose as to which solution, Theis or Jacob, would be more realistic to use in evaluating recharge. The consensus was that the limiting case of the Jacob method would have more applicability to this specific case. This is because the Theis method requires the use of observation wells spaced at relatively large distances from the pumping well. The Jacob method has more application in instances where the distance (r) to an observation well is very small and the test is carried out over long time intervals. In this specific project, the recharge bores were used for monitoring changes in water level, so the distance to the observation point is the radius of the bore.

4. The Jacob equation takes the form:

$$s = \frac{2.30\ Q}{4\pi\ T} \log \frac{2.25\ T}{r^2\ S} + \frac{2.30\ Q}{4\pi\ T} \log t$$

s = water level change at time t
T = transmissibility in gallons per day per foot
Q = discharge (recharge) in gallons per day
t = time in days
S = storage coefficient, dimensionless

5. A plot of water level change versus the logarithm of t is constructed. In a dewatering well problem, this plot is essentially a straight line. In a recharge situation, the line curves but tends to approach a straight line. Where this curved line approaches

the straight line, the Jacob equation can be solved using the water level difference over one log cycle:

$$s_1 = \frac{2.30\ Q}{4\pi\ T} \left(\log \frac{2.25\ T}{r^2\ S} + \log t_1\right)$$

$$s_2 = \frac{2.30\ Q}{4\pi\ T} \left(\log \frac{2.25\ T}{r^2\ S} + \text{Log}\ t_2\right)$$

$$s_2 - s_1 = \Delta s = \frac{2.30\ Q}{4\pi\ T} \left[\left(\log \frac{2.25\ T}{r^2\ S} + \log t_2\right) - \left(\log \frac{2.25T}{r^2\ S} + \log t_1\right)\right]$$

$$\Delta s = \frac{2.30\ Q}{4\pi\ T} \log t_2/t_1 \qquad \text{let } t_2 = 10\ t_1$$

$$s = \frac{2.30\ Q}{4\pi\ T}$$

Using the above equation, T can be evaluated for the various phases of the recharge tests, bore "B"-initial, bore "B"-cleaned, bore "B" with screen, and the trench cleaned by the surge and pump method. The following T values obtained from this analyses were:

Bore B initial T = 602 g/d/ft
Bore B cleaned T = 540 g/d/ft
Bore/well "B" screen T = 1,220 g/d/ft
Trench cleaned T = 540 g/d/ft

It was expected that bore "B" cleaned would yield a higher T value than bore "B"-initial. The data in Figures 7 and 10 show the bore "B"-cleaned initially took a larger volume of water, with substantially less head change than bore "B"-initial; however, the T value is a function of the total test period, and there was an obvious decrease in infiltration rate as the test progressed, which caused the overall T value to lower significantly. This apparent lack of difference in the two test results is probably best explained by the fact that extremely dirty water was introduced into the second test. Erosion problems in the bog during pumping caused a high siltation problem, and it is conservatively estimated that a minimum of four cubic feet of silt was deposited in the bore during the second run. This fine-grained sediment clogged the voids in the aquifer material at the recharge point, substantially decreasing the aquifer's capacity to transmit water.

6. The change in the T value achieved as a result of the installation of the well screen is significant in that the capacity of the bore to transmit recharge water was increased by about 200 percent. Trench recharge is not significantly different compared to a bore, even though the cross-sectional surface for recharge is considerably larger.

7. The Jacob equation can also be used to predict how much water can be recharged over a given period of time at a recharge point. It must be kept in mind, however, that these predictions are based on adding water to an existing aquifer system in which there is a net increase in the amount of water transmitted by the system. In the operation of the pilot containment system, recharge will be in equilibrium with the amount of water removed and treated; therefore, no net change in water volume moving through the aquifer will occur.

8. In using the Jacob equation for making these predications, under worst case conditions, a value for S (storage coefficient) needs to be determined. Calculating an S using the Jacob or Theis method results in a wide range of values. This fact alone indicates the need for caution in applying well-flow equations to recharge. Values for S generally range between 0.05 and 0.3. The simulation modeling of the north boundary area by the USGS used a value of 0.25 for S. In our further discussions with Dr. Stan Robson of the USGS, it was felt that storage coefficient is really not a factor in recharge; but in order to make the equations work, a high S should be used. Therefore, we accept S = 0.25 as the value to be used in the equation:

$$\Delta s = \frac{2.30\ Q}{4\pi\ T} \log \frac{2.25\ Tt}{r^2\ S}$$

9. If we allow a maximum head rise in an individual recharge well to be 10 feet, we can calculate the allowable recharge rate (Q) that can be used over a given period of time.

(Time) t = 30 days	Q = 9.3 gpm
t = 60 days	Q = 8.7 gpm
t = 90 days	Q = 8.4 gpm

10. It must again be stressed that these head rises would occur under worst case conditions in which there is a net gain in the amount of water to be transmitted by the aquifer. Under actual operating conditions of the pilot containment system, limited or minimal head

rise above the presently existing water table fluctuations would be expected.

11. The results of the recharge testing program indicate that the preferred design is to employ a series of wells at least 16 inches in diameter. The screened interval in these wells should be through the entire thickness of the aquifer.

12. The number of recharge wells required will be based on the volume and distribution of water flowing past the 1,500 foot containment system and the worst case head rise in the wells. The volume of water flowing past the 1,500 foot alignment has been calculated by USGS, WES, and the Geohydrology Division, IR, to range from 40 to 75 gpm. The high side 75 gpm can be accommodated capacity-wise by nine wells. However, to achieve the required uniform distribution back into the aquifer using an effective radius of influence of 125 feet for each well, 12 recharge wells would be required. The additional wells would also permit the shutting down of two to three wells for redevelopment should the infiltration rate be reduced to unacceptable levels, with a neglible influence on distribution recharge for short periods of time.

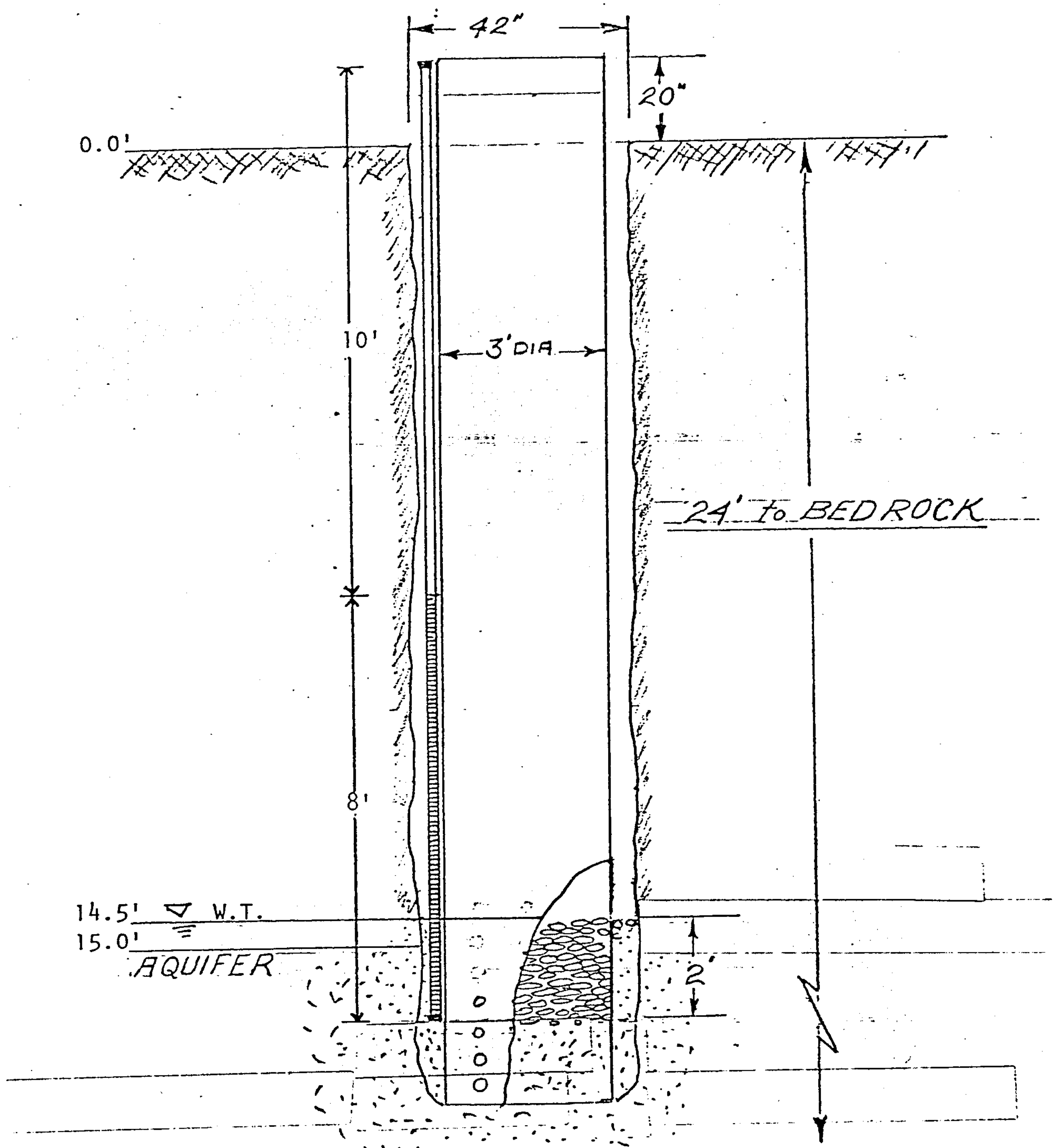
13. The screened recharge wells have a significantly greater infiltration rate for square foot of recharge area than either the plain recharge bore or the trench. The additional cost of the screened well would be partially offset by the decrease in well-development effort, increase in the number of bores if screens are not used, and increase in maintenance effort to maintain a constant infiltration rate on trenches or plain bores.

14. The screened well also facilitates the collection of flow-recharge data and control of constant-Q's which are required to develop long-term pilot containment data.

IV. RECOMMENDATIONS - Taking into consideration: (a) Ease of maintenance and operation, (b) Ability to acquire accurate operational test data, (c) The number of recharge points required to reproduce the natural aquifer distribution, and (d) The ability to balance the dewatering and recharge operations to accommodate seasonal variation on aquifer flow, it is recommended that a system of 12, 16 inch diameter wells, installed and consistent with practices normally used in developing a water supply well, be employed in the north boundary pilot containment system to recharge the water from the water treatment facility back into the aquifer.

RECHARGE TEST BORE
LOCATION-B

FIGURE 1



- Bottom of 3 ft. Dia. casing is perforated with 10 rows of 4 holes each 1 inch in diameter.
- A 2 inch PVC monitoring well with an 8 ft perforated section was set outside the 3 ft diameter casing on the down gradient side.
- Two additional monitoring wells with 12 ft perforated sections were located 5' and 25' down gradient from the edge of the 3 ft diameter casing.
- 3/8 to 3/4" washed gravel, 2' thick down from water table

FIGURE 2
PILOT CONTAINMENT SYSTEM & LOCATION OF TEST BORES

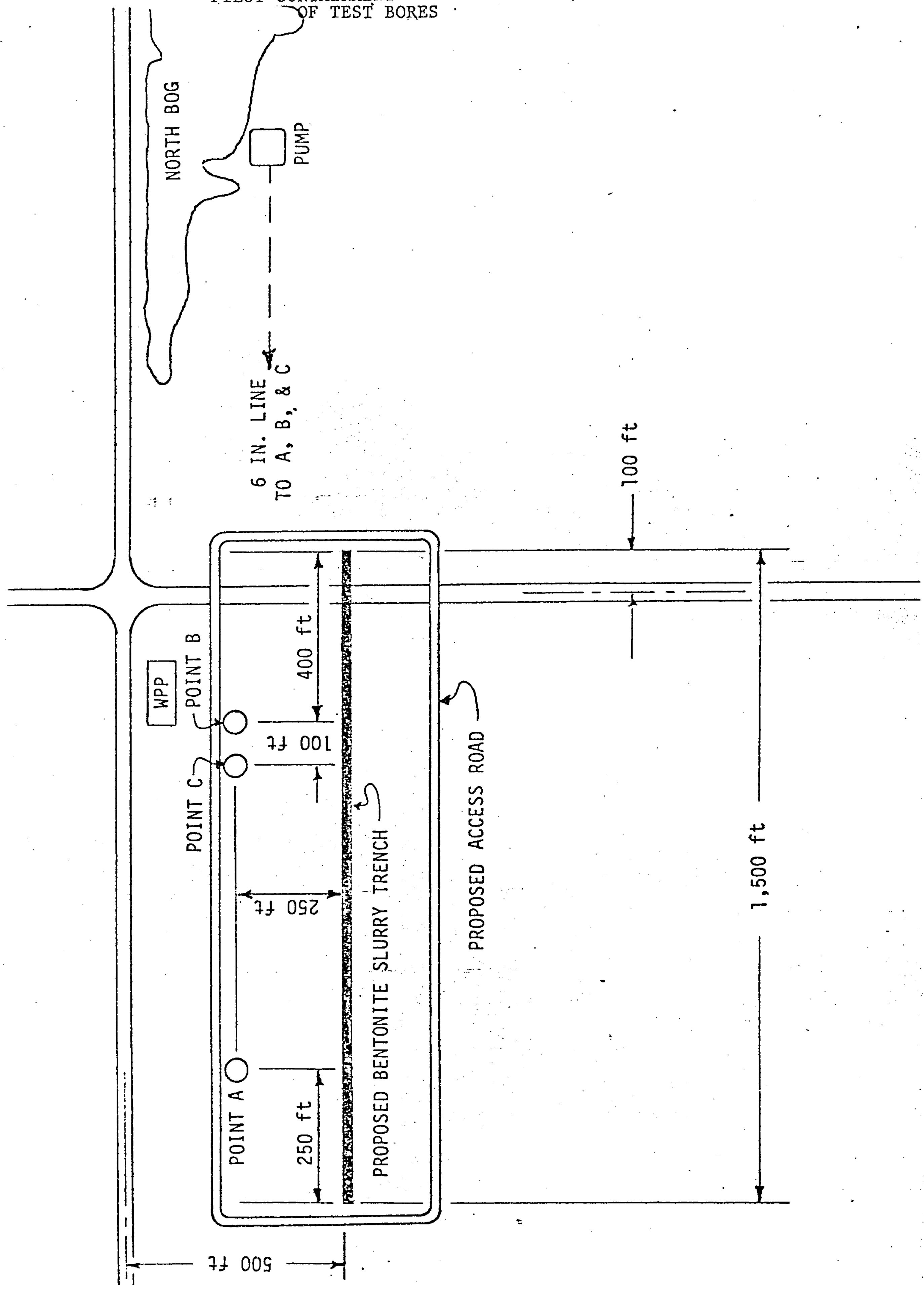
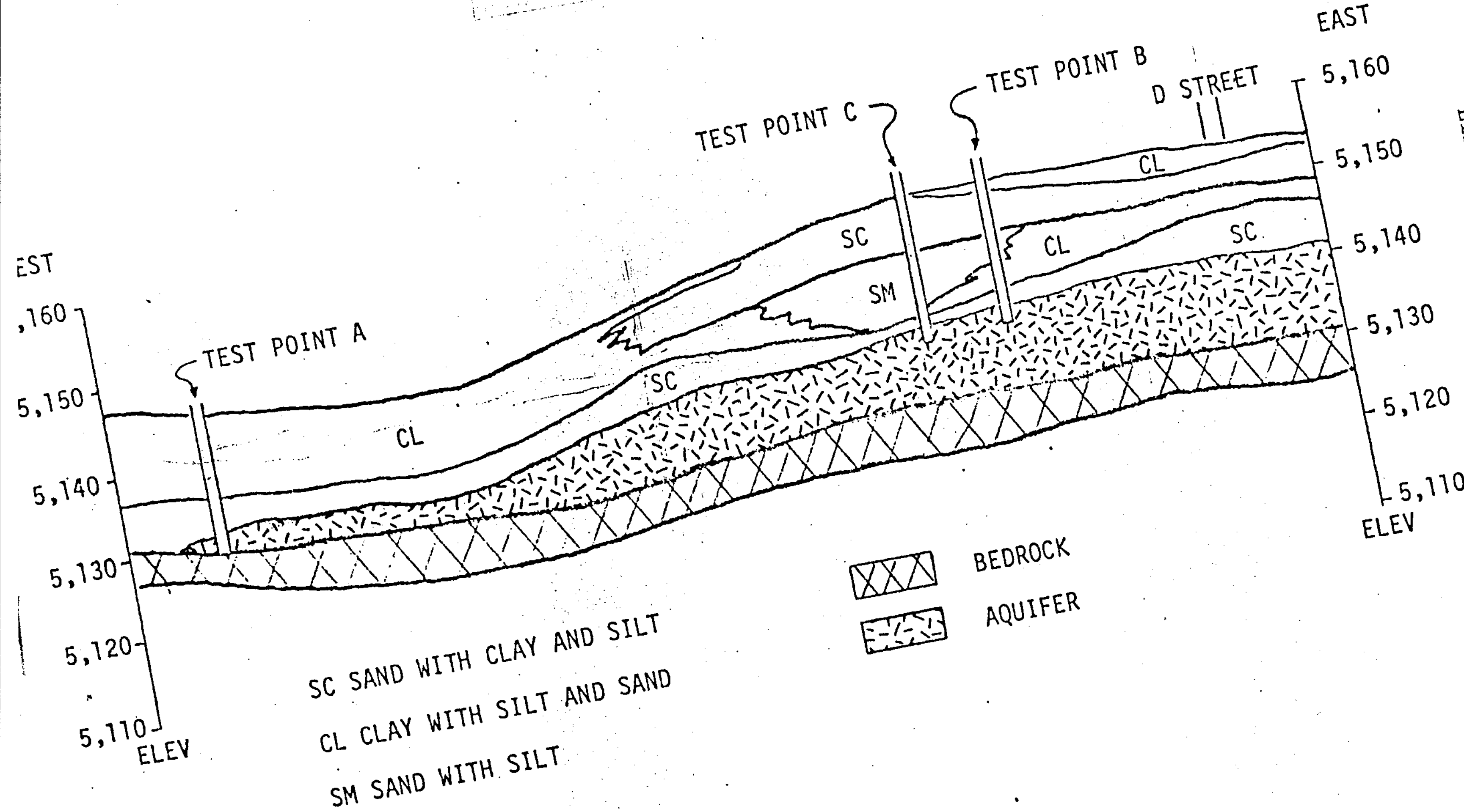


FIGURE 3
STRATIGRAPHIC CROSS SECTION OF RECHARGE
LINE WITH TEST BORE LOCATIONS



IV. RECOMMENDATIONS - Taking into consideration: (a) Ease of maintenance and operation, (b) Ability to acquire accurate operational test data, (c) The number of recharge points required to reproduce the natural aquifer distribution, and (d) The ability to balance the dewatering and recharge operations to accommodate seasonal variating on aquifer flow, it is recommended that a system of 12, 16 inch diameter wells, installed and consistent with practices normally used in developing a water supply well, be employed in the north boundary pilot containment system to recharge the water from the water treatment facility back into the aquifer.

RECHARGE TEST TRENCH

FIGURE 4

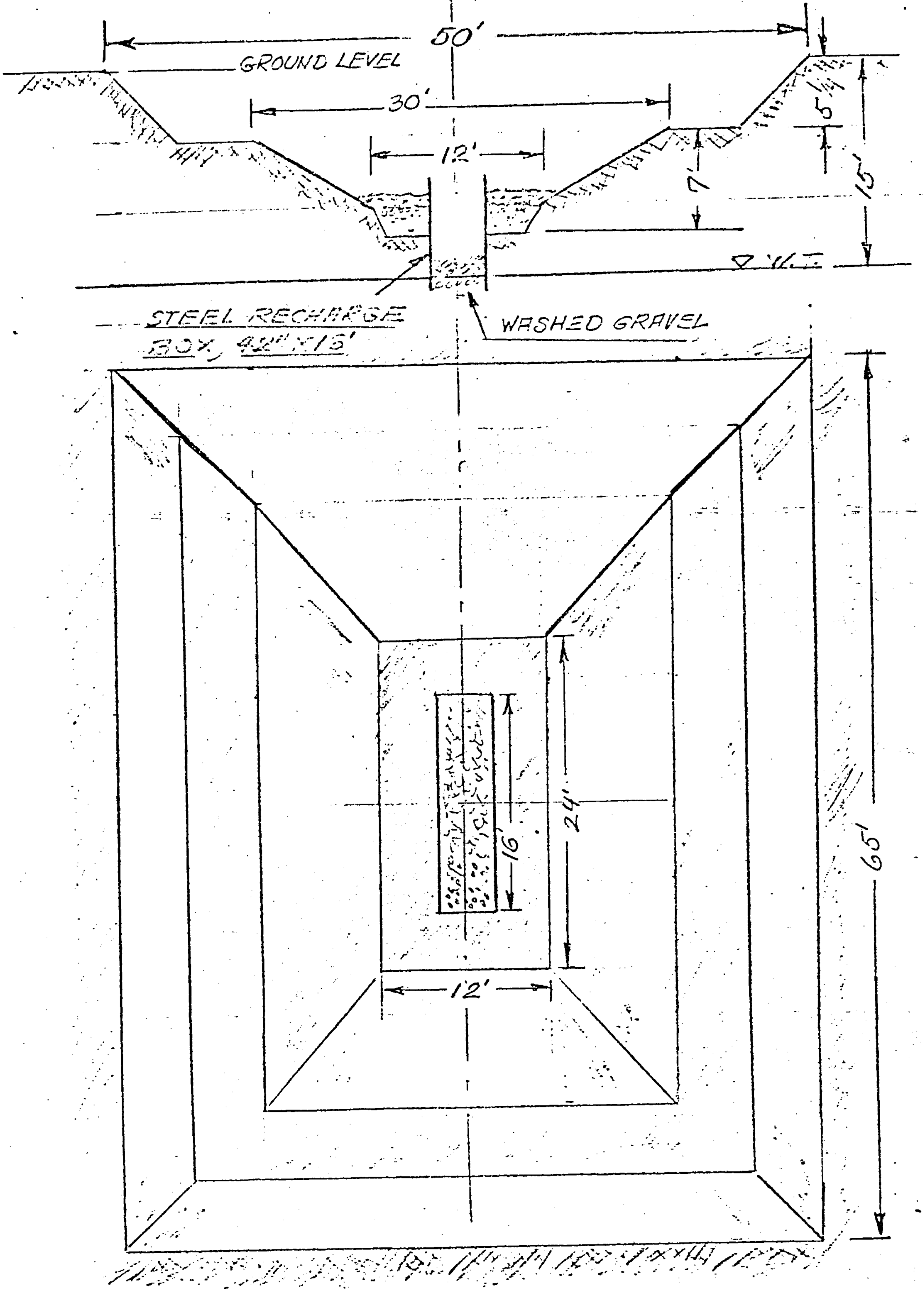
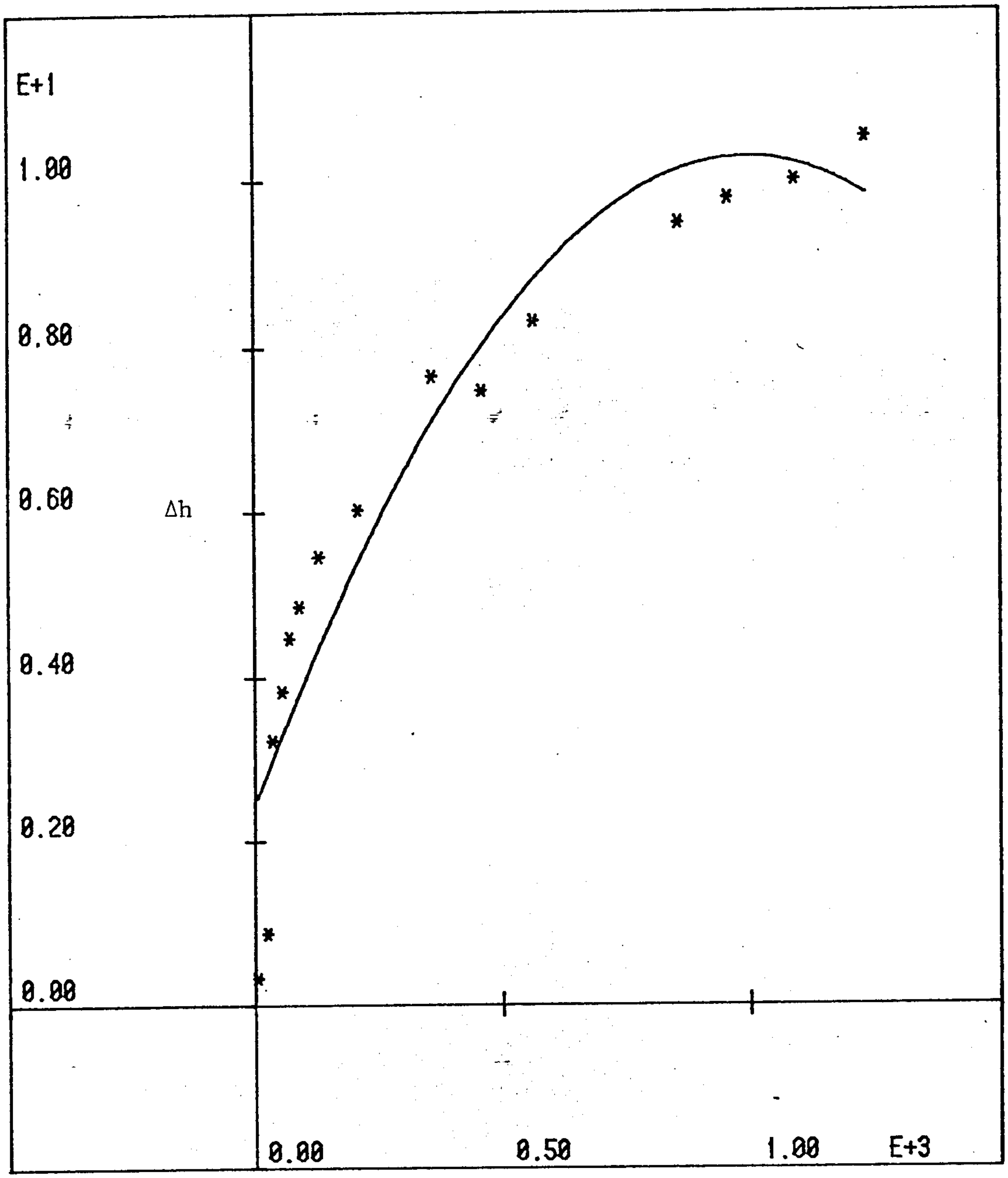


FIGURE 5
GRAPH OF HEAD CHANGE VERSUS TIME
FOR BORE "B" - INITIAL



Time (minutes)

FIGURE 6
GRAPH OF HEAD CHANGE VERSUS TIME FOR
BORE "C" INITIAL

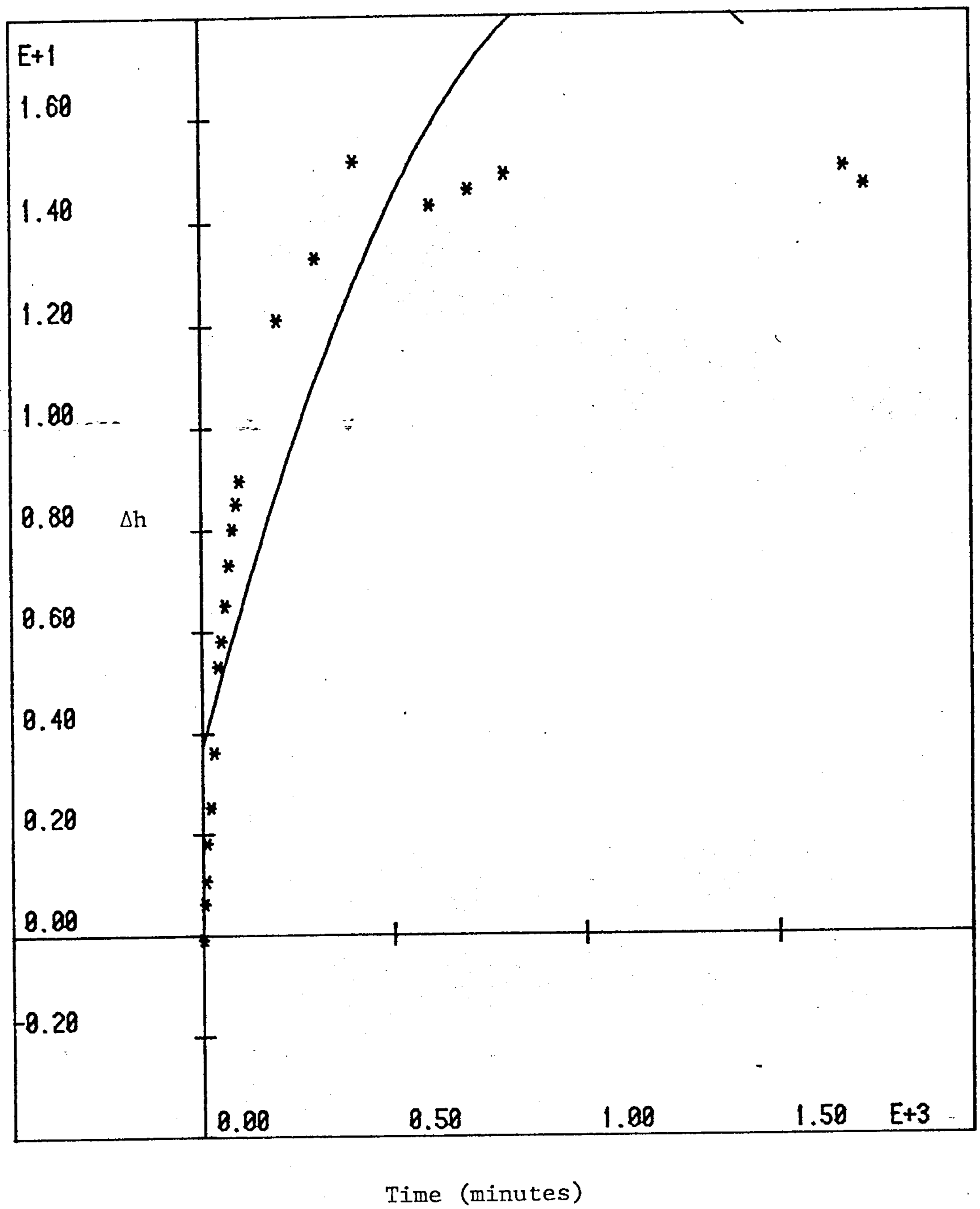
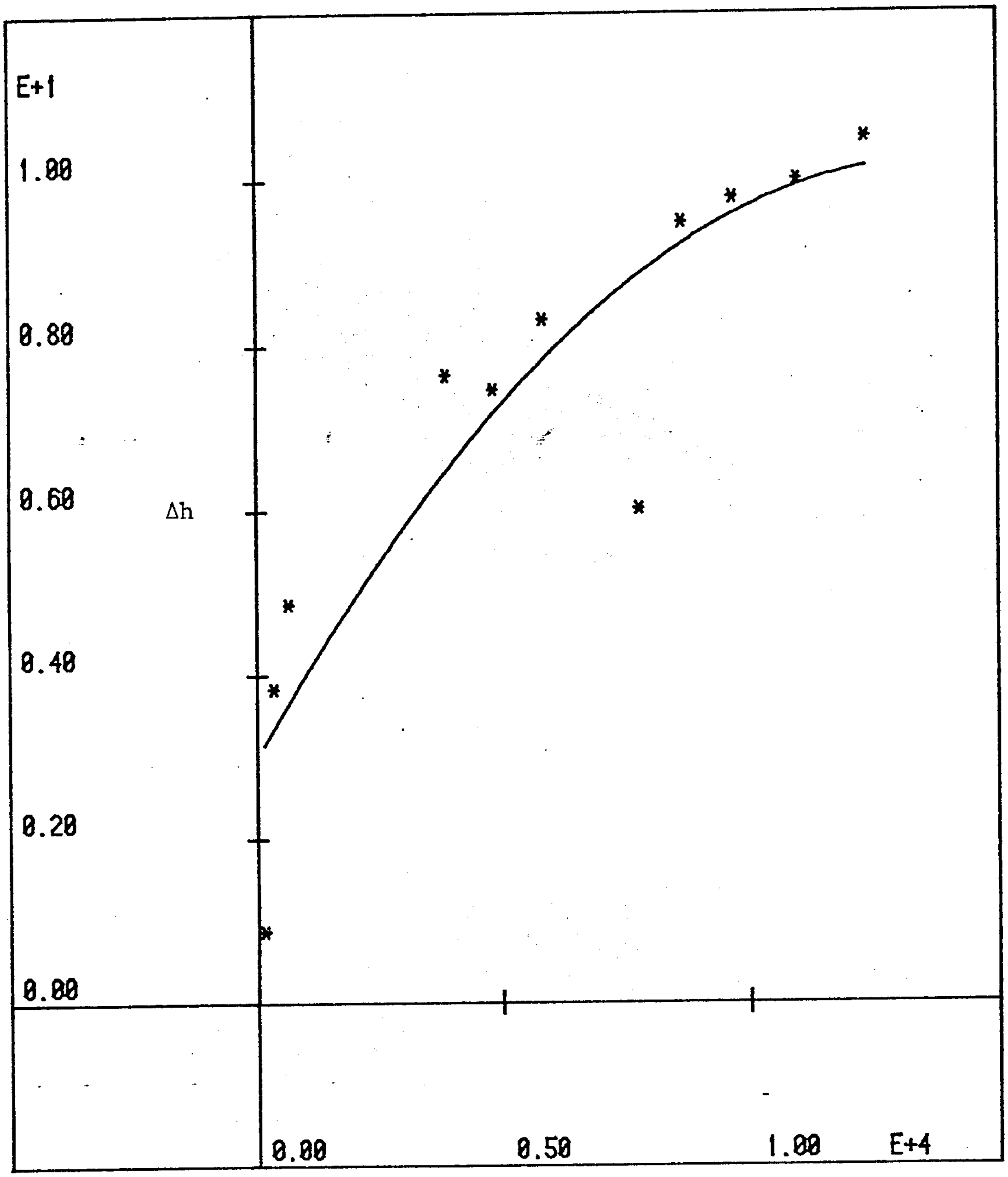
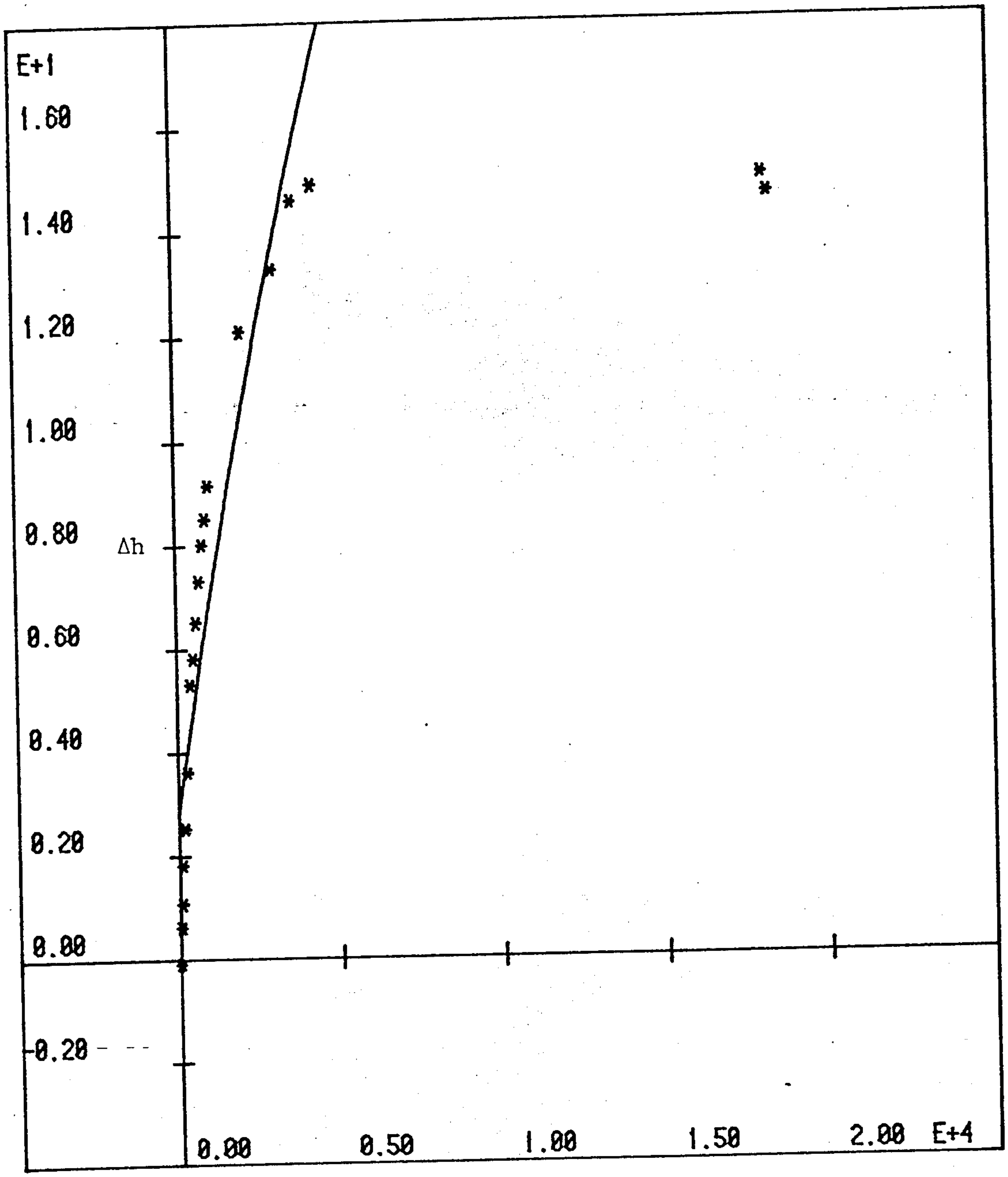


FIGURE 7
GRAPH OF HEAD CHANGE VERSUS TOTAL
RECHARGE FOR BORE "B" INITIAL



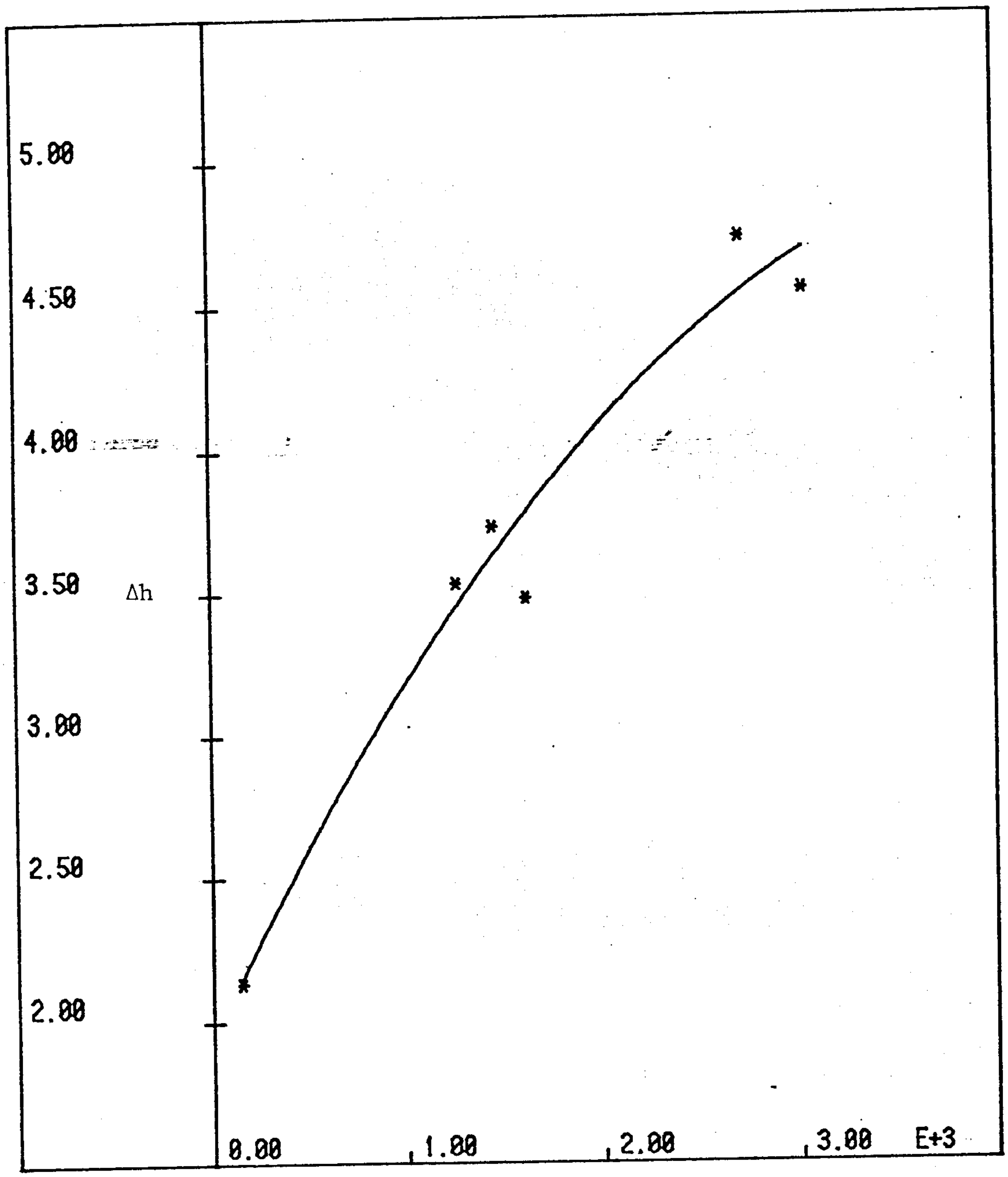
Q Total (gallons)

FIGURE 8
GRAPH OF HEAD CHANGE VERSUS TOTAL
RECHARGE FOR BORE "C" INITIAL



Q Total (gallons)

FIGURE 9
GRAPH OF HEAD CHANGE VERSUS
TIME FOR BORE "B"-CLEAN



Time (minutes)

FIGURE 10
GRAPH OF HEAD CHANGE VERSUS TOTAL
RECHARGE FOR BORE "B"-CLEAN

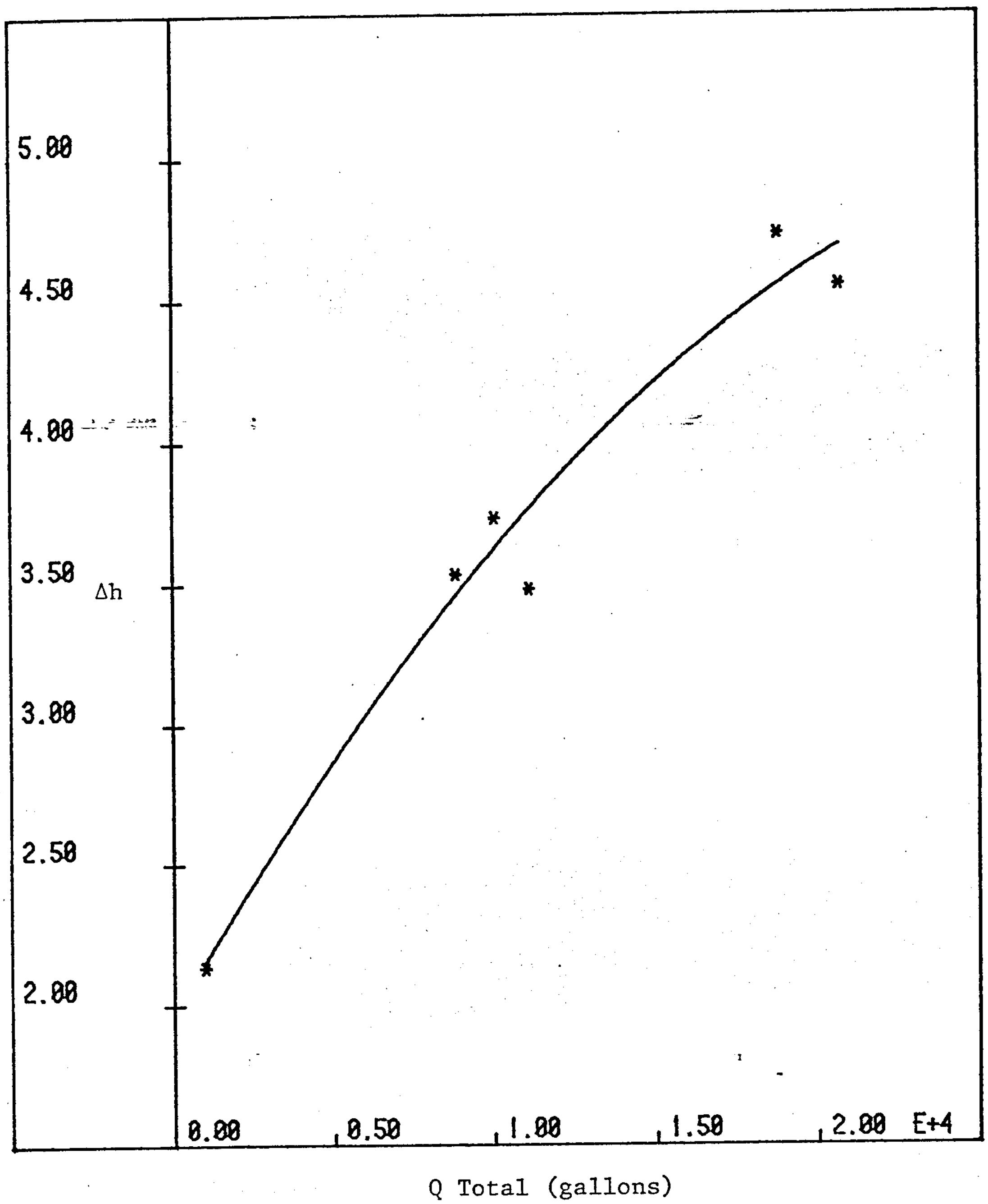
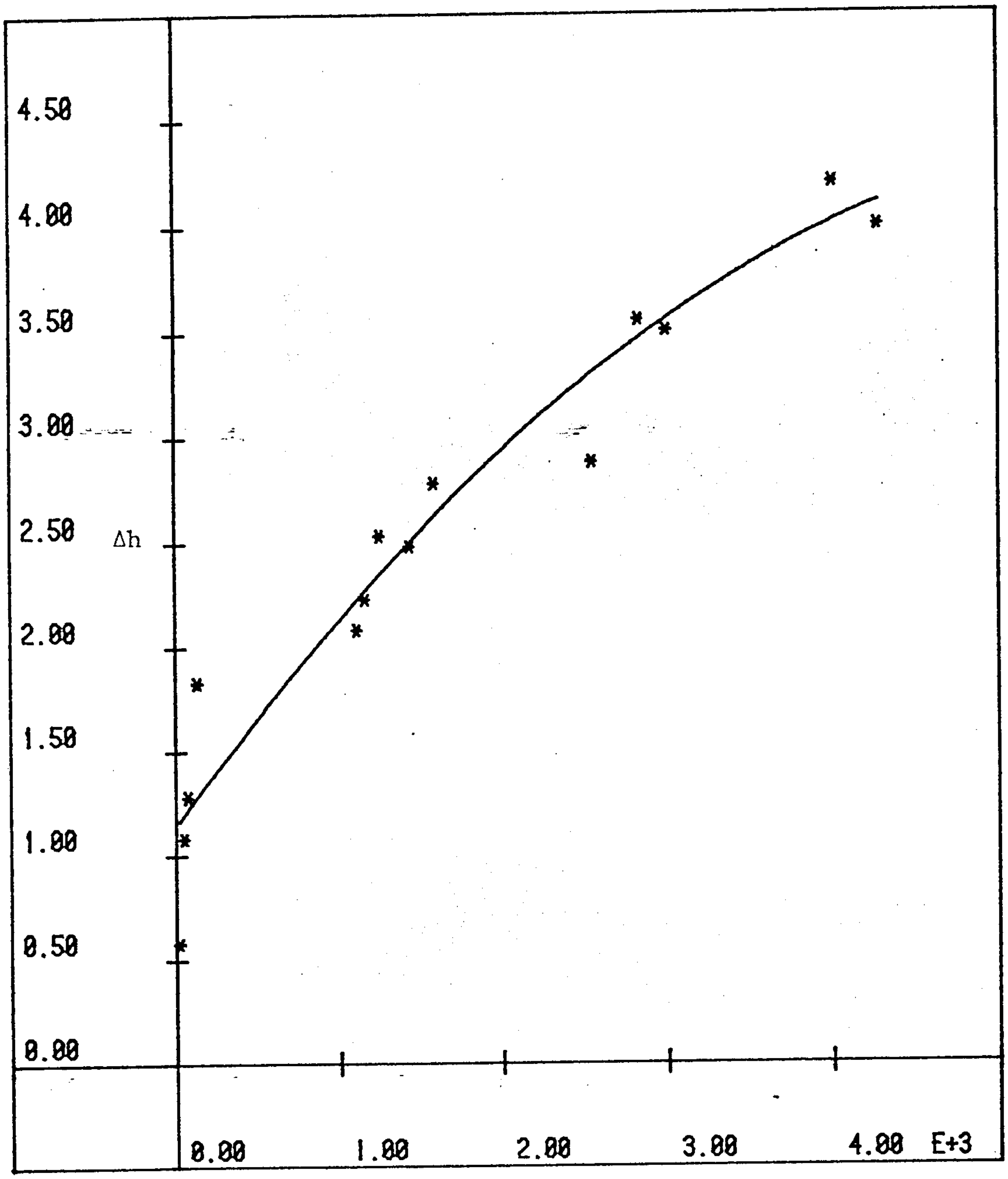
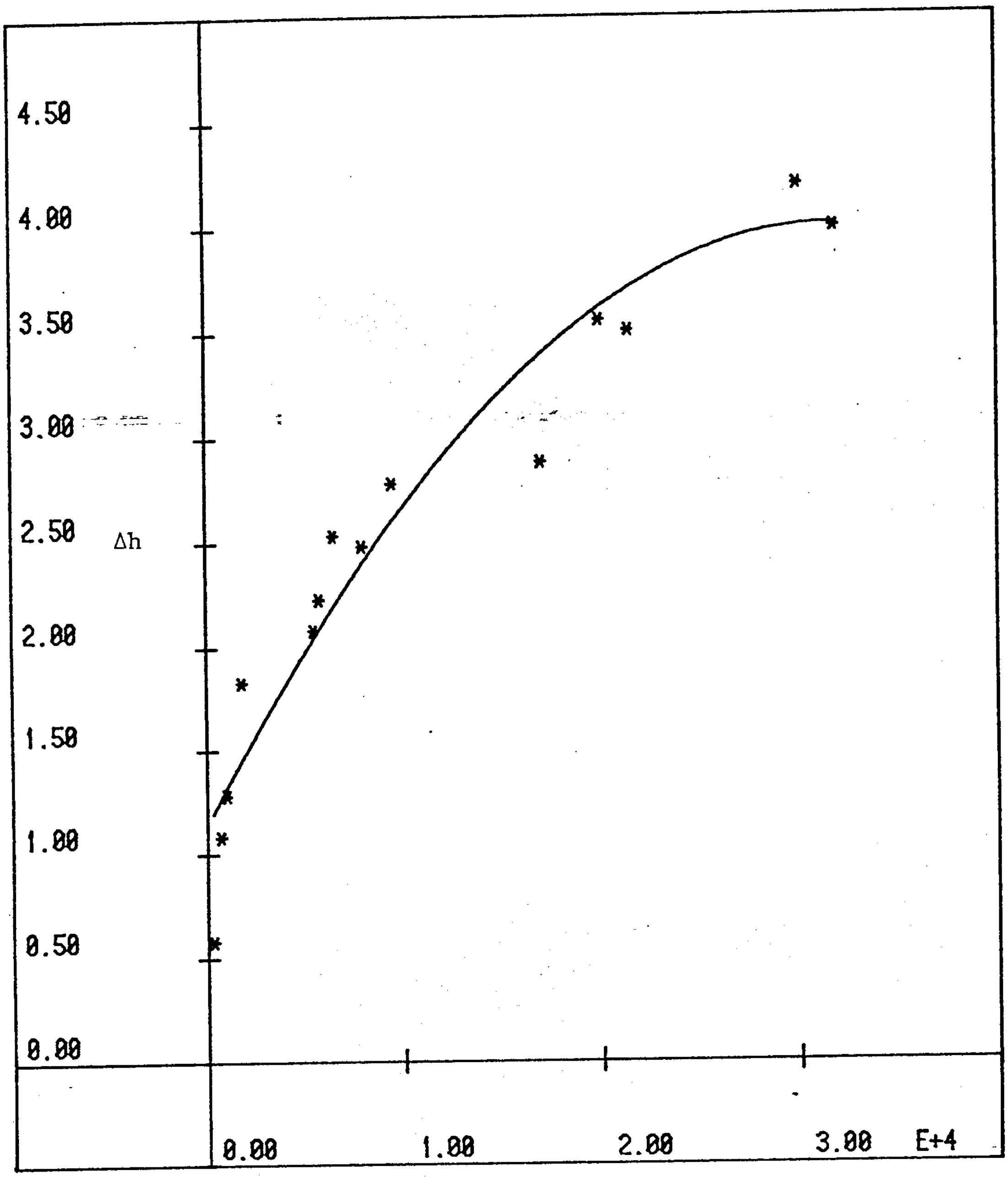


FIGURE 11
GRAPH OF HEAD CHANGE VERSUS
TIME FOR CLEANED TRENCH



Time (minutes)

FIGURE 12
GRAPH OF HEAD CHANGE VERSUS TOTAL
RECHARGE FOR CLEANED TRENCH



Q Total (Gallons)

FIGURE 13

RECHARGE TEST BORE/WELL B

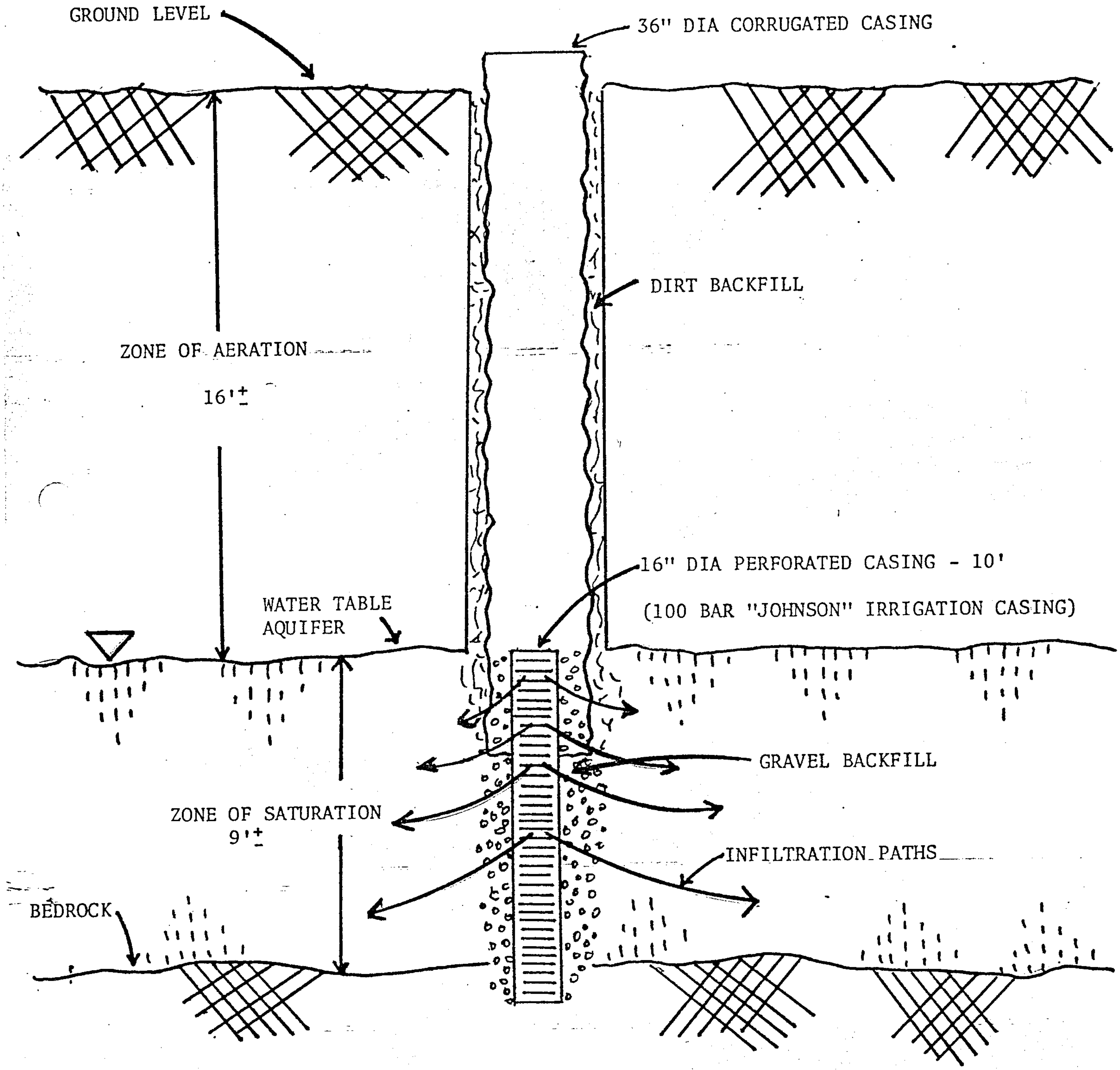
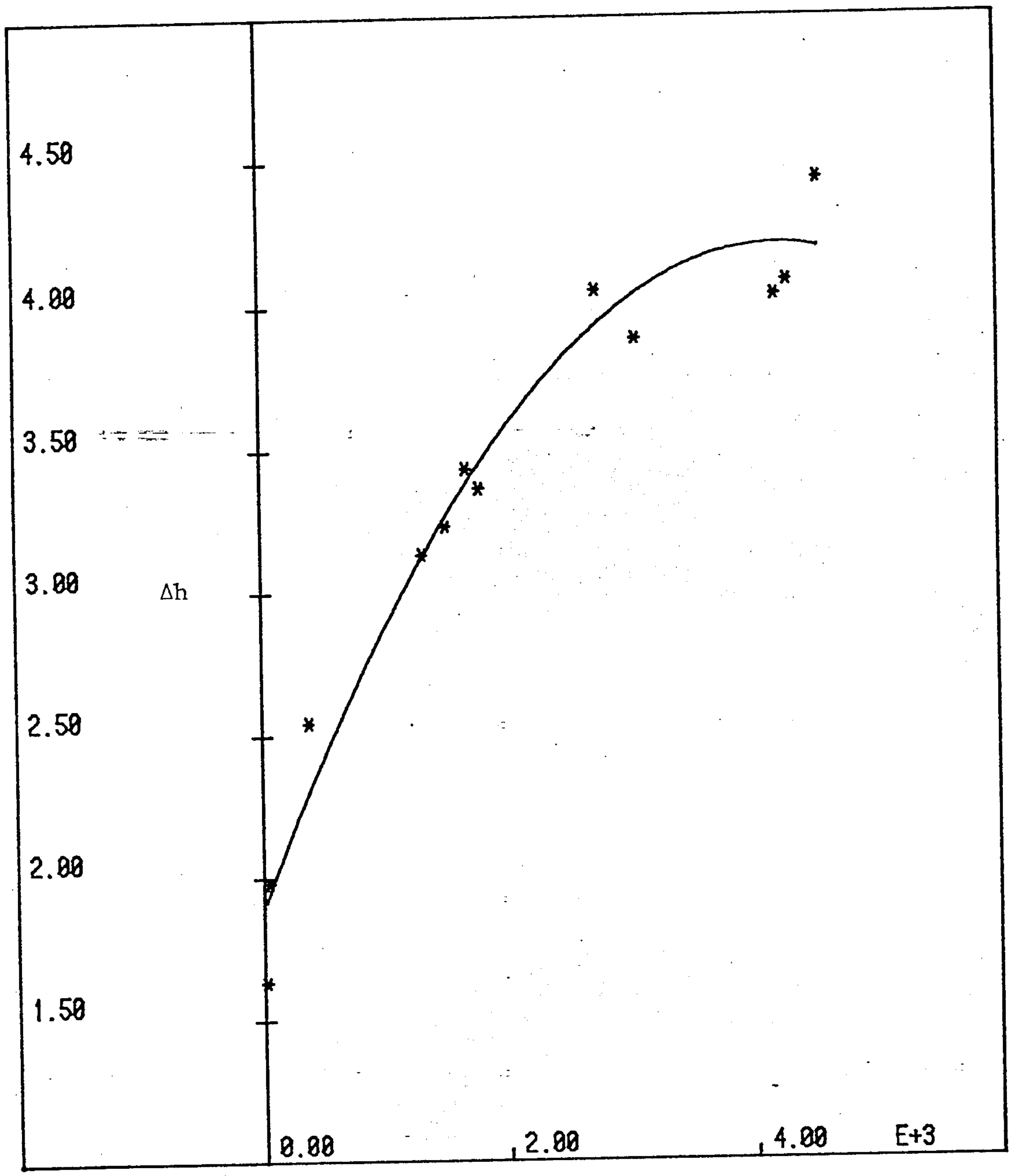
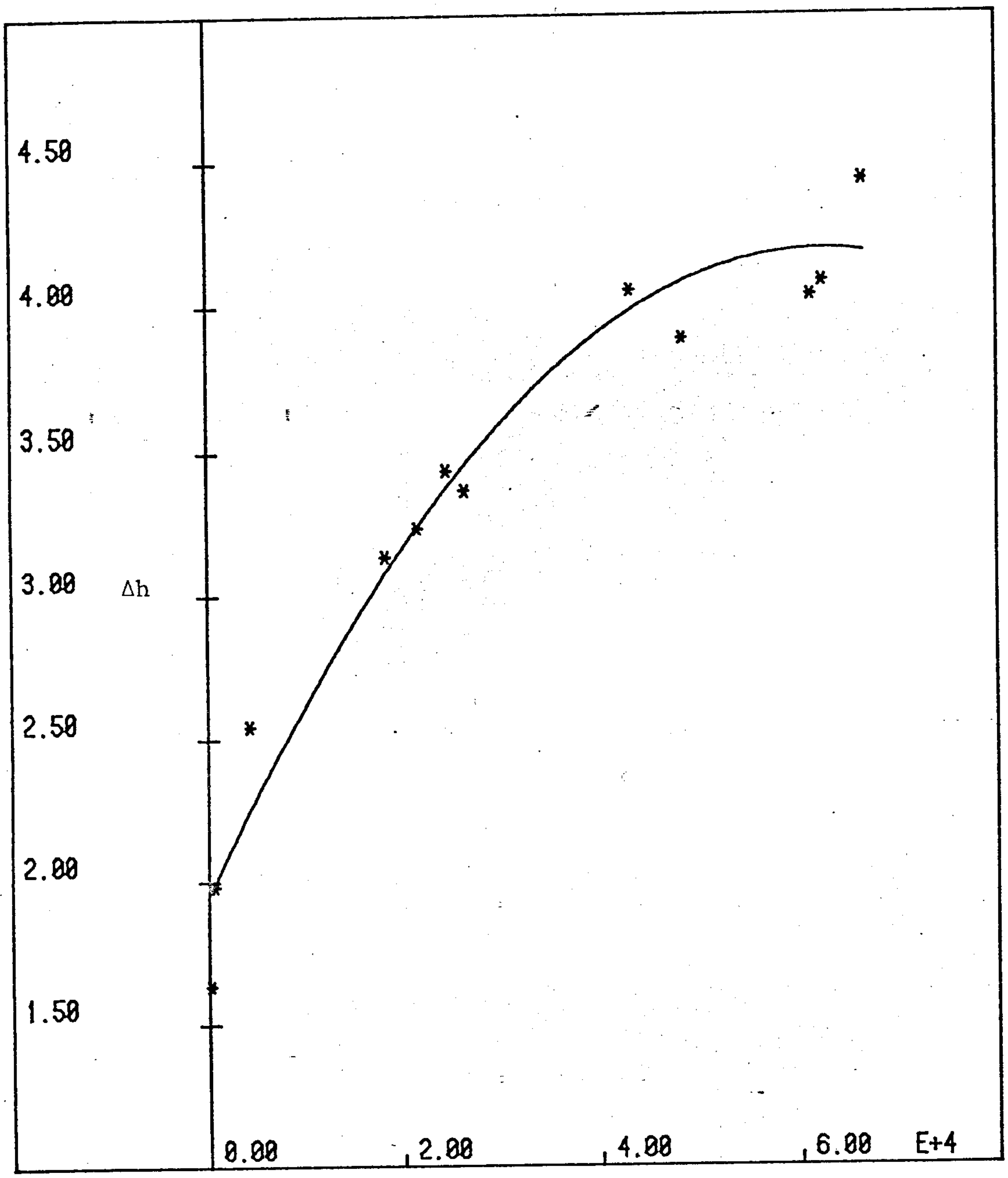


FIGURE 14
GRAPH OF HEAD CHANGE VERSUS
TIME FOR BORE/WELL "B"



Time (minutes)

FIGURE 15
GRAPH OF HEAD CHANGE VERSUS
TOTAL RECHARGE FOR BORE/WELL "B"



Q Total (gallons)